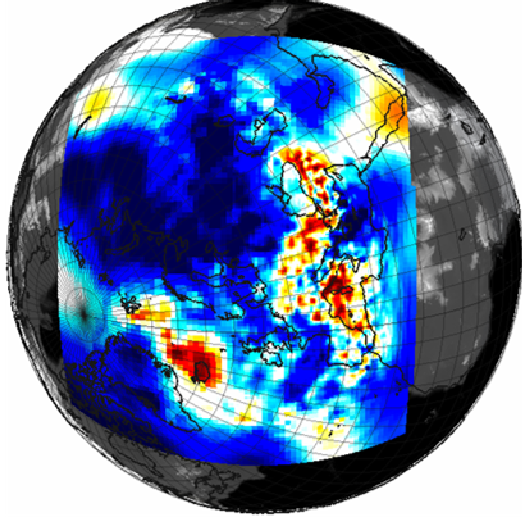


# MULTI-SCALE WAVEFORM TOMOGRAPHY OF EUROPE AND WESTERN ASIA

Linking crustal tectonics with mantle dynamics



**Andreas Fichtner,**

**Paul Cupillard & Jeannot Trampert**

in collaboration with Rob Govers, Erdinc Saygin, Tuncay Taymaz, Antonio Villaseñor & Rinus Wortel

# MOTIVATION 1: SCALE-DEPENDENCE OF TOMOGRAPHIC PERCEPTION

**Unresolvable small-scale structure may lead to incorrect images of large-scale structure.**

- small-scale near-receiver velocity structure trades off with large-scale Q structure
  - lack of correlation between various 3D Q models
- small-scale isotropic crustal structure trades off with large-scale anisotropy
  - discrepant inferences on strength, depth-extent and sign of anisotropy

...

## MOTIVATION 2: IMAGING CRUST-MANTLE INTERACTION

**Incorrect crustal structure maps into apparent mantle heterogeneity and vice versa.**

- mantle tomography commonly uses crustal corrections
  - inadequate crustal models map into artificial mantle structure, especially anisotropy
- crustal studies often ignore the 3D heterogeneous mantle
  - insufficiently accurate crustal models that do not explain the full range of seismic data

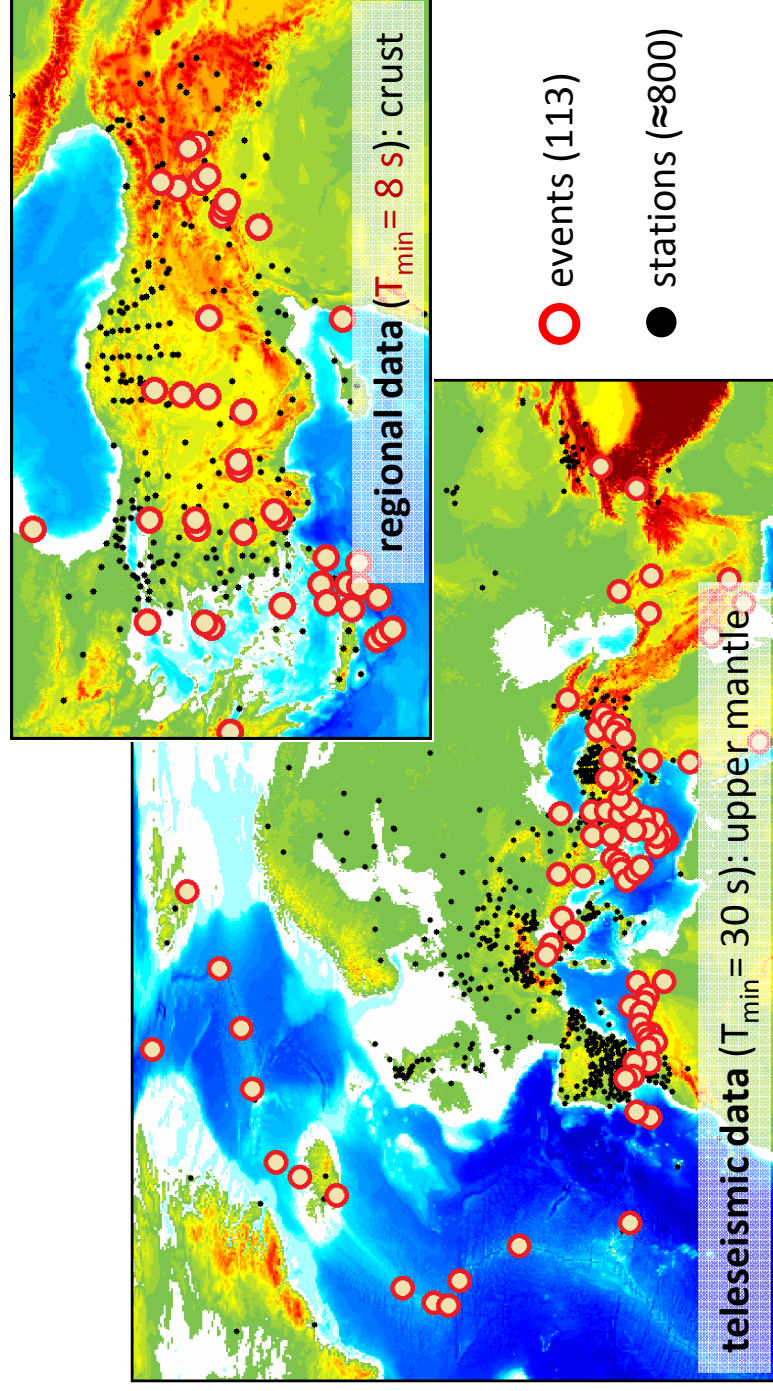
# MOTIVATION 1: SCALE-DEPENDENCE OF TOMOGRAPHIC RESOLUTION 2: IMAGING CRUST-MANTLE INTERACTION

## WHAT IS NEEDED:

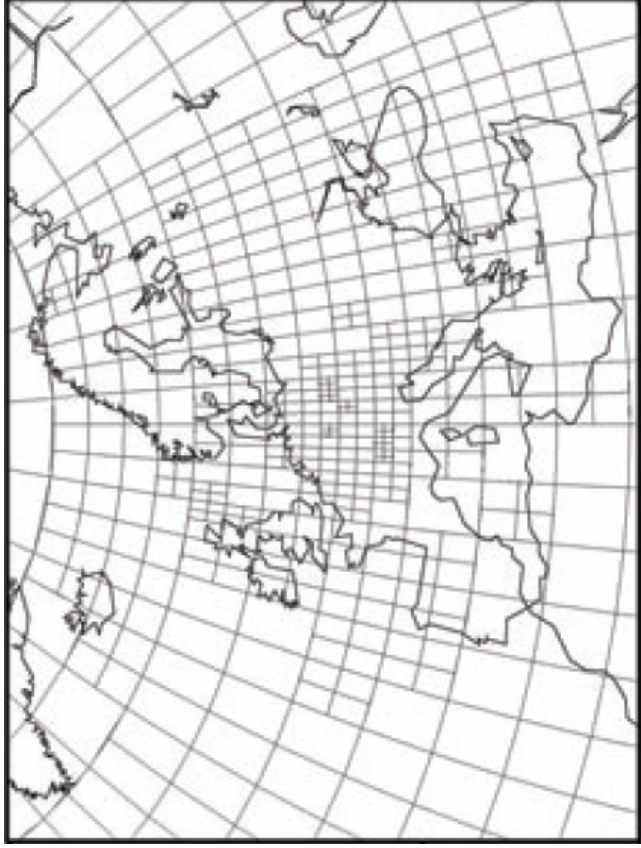
- **simultaneous inversion for crustal and mantle structure**
  - resolve crust-mantle inconsistencies
  - No more crustal and mantle models! One Earth!
- **integration of data on various scales**
  - local and regional higher-frequency data for the crust
  - continental- to global-scale data (at lower frequencies) for the mantle

## DATA:

- Local and regional data are not always available ...
- ... but there are very good starting points



## MULTI-SCALE APPROACHES:



Schäfer, Boschi & Kissling, *GJI*, 2011.

### Other examples:

Widiyantoro & van der Hilst, *GJI*, 1997.

Bijwaard et al., *JGR*, 1998.

Debayle & Sambridge, *JGR*, 2004.

Boschi et al., *GJI*, 2004.

Nolet & Montelli, *GJI*, 2005.

Bodin & Sambridge, *GJI*, 2009.

### Semi-analytic forward problem solution

ray theory, normal modes, etc. ...

- almost standard
- mesh refinement where dense regional data are available
- geographic equalisation of resolution



# MULTI-SCALE APPROACHES:

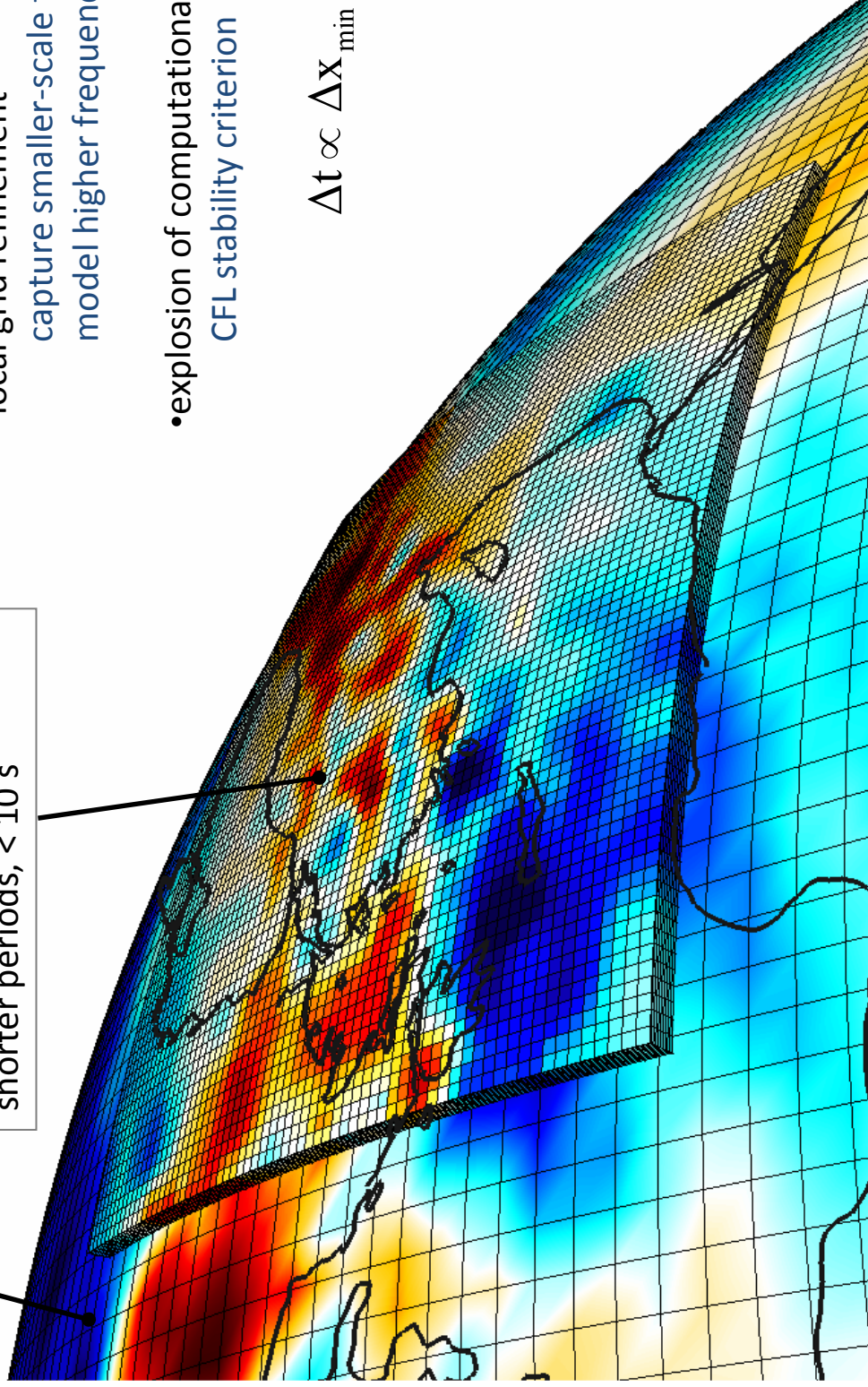
longer-wavelength structure  
longer periods, > 30 s

shorter-wavelength structure  
shorter periods, < 10 s

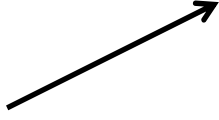
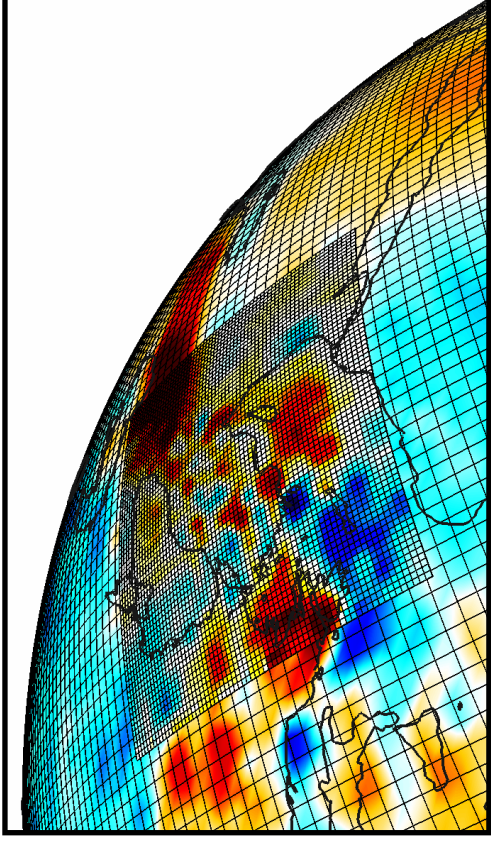
**Numerical forward problem solution**  
finite-differences, spectral-elements, etc. ...

- local grid refinement  
capture smaller-scale features  
model higher frequencies
- explosion of computational requirements  
CFL stability criterion

$$\Delta t \propto \Delta x_{\min}$$

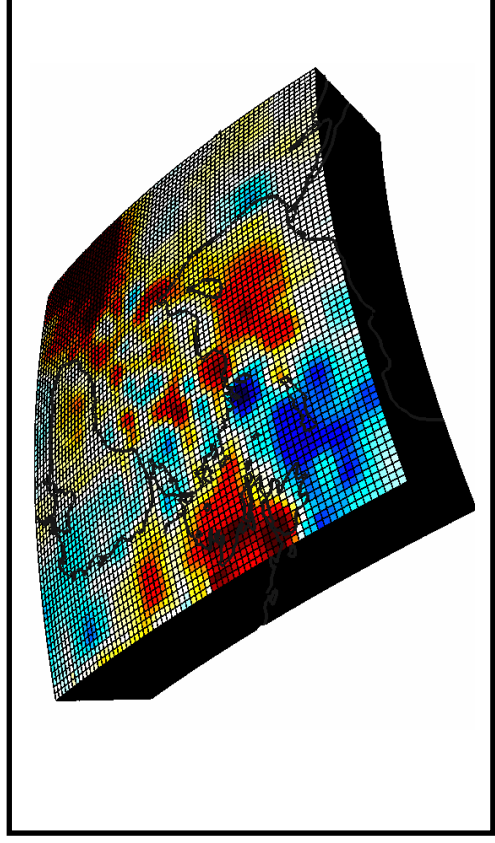
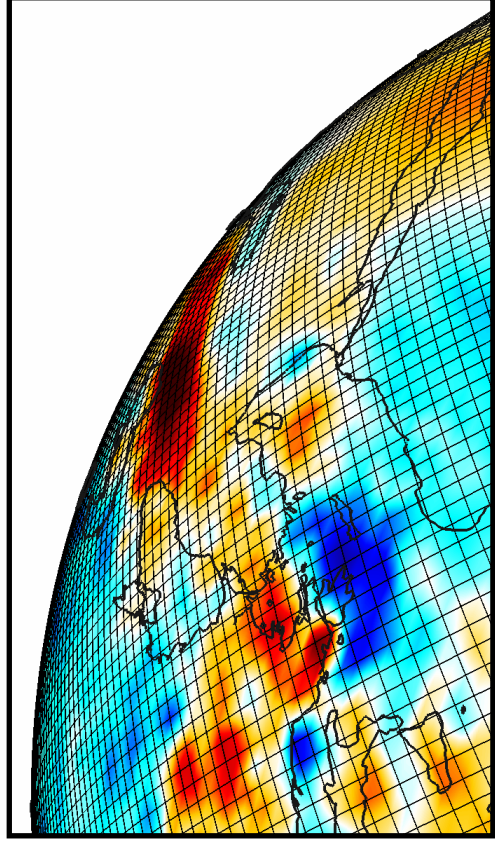


# DOMAIN-DECOMPOSITION AND MULTIPLE FORWARD PROBLEMS:



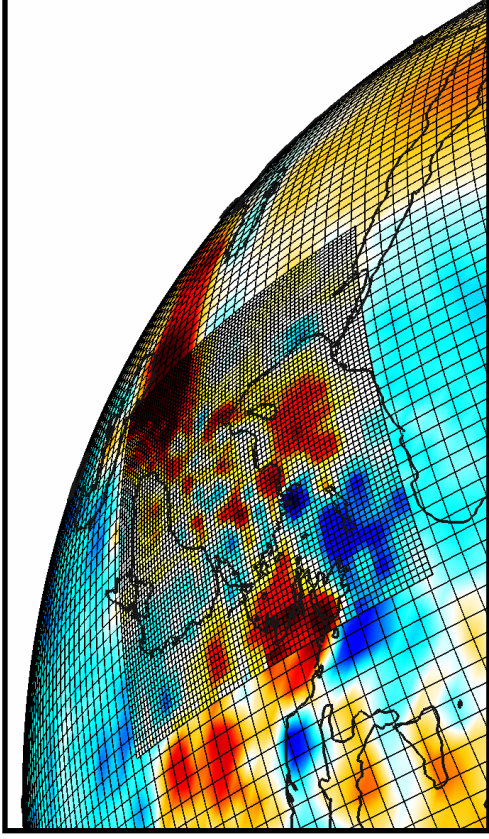
coarse long-wavelength model  
large volume  
large grid size and time step

fine short-wavelength model  
small volume  
small grid size and time step





# DOMAIN-DECOMPOSITION AND MULTIPLE FORWARD PROBLEMS:



detailed

requires **upscaling**

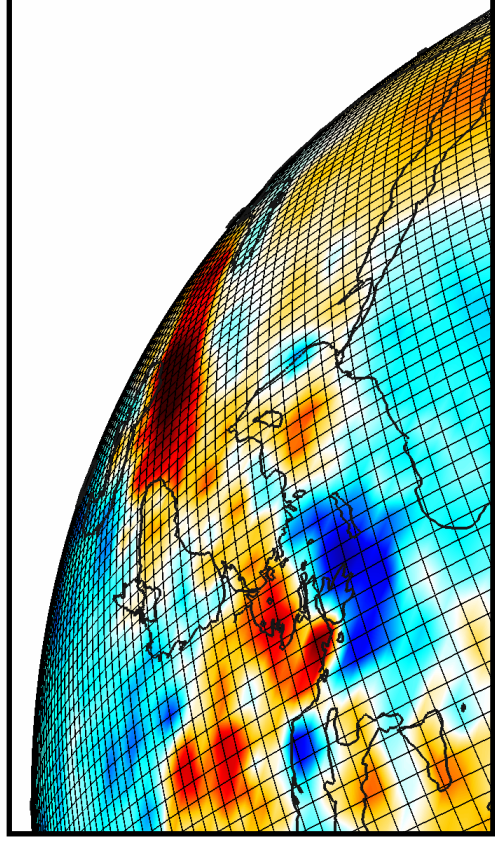
smooth

Backus averaging (Backus, 1962)

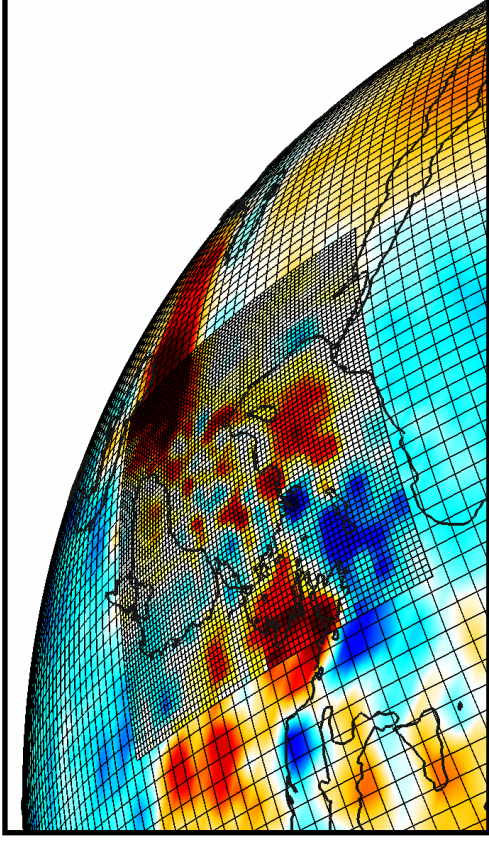
homogenisation

(Capdeville et al., 2010; Guillot et al., 2010)

→ **apparent anisotropy**



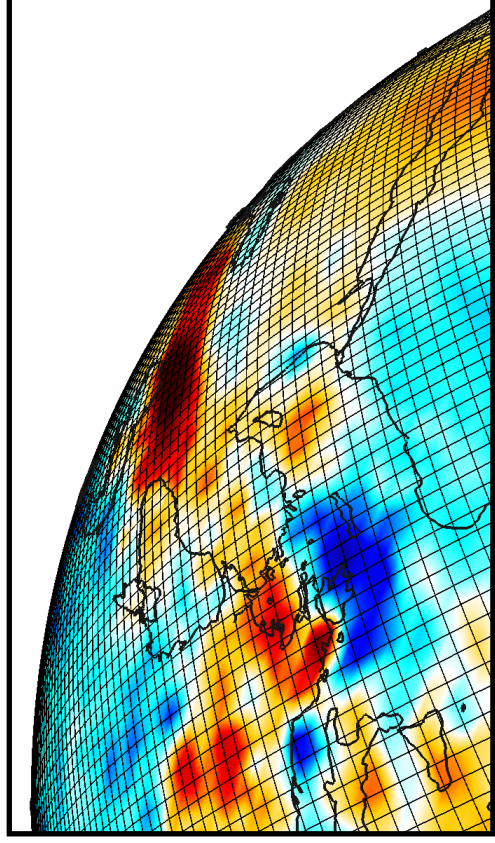
# DOMAIN-DECOMPOSITION AND MULTIPLE FORWARD PROBLEMS:



detailed

interpolation

smooth



upsampling & interpolation



iterative joint inversion  
teleseismic & regional data for  
local and deep structure

# APPLICATION:

## Technical specifications

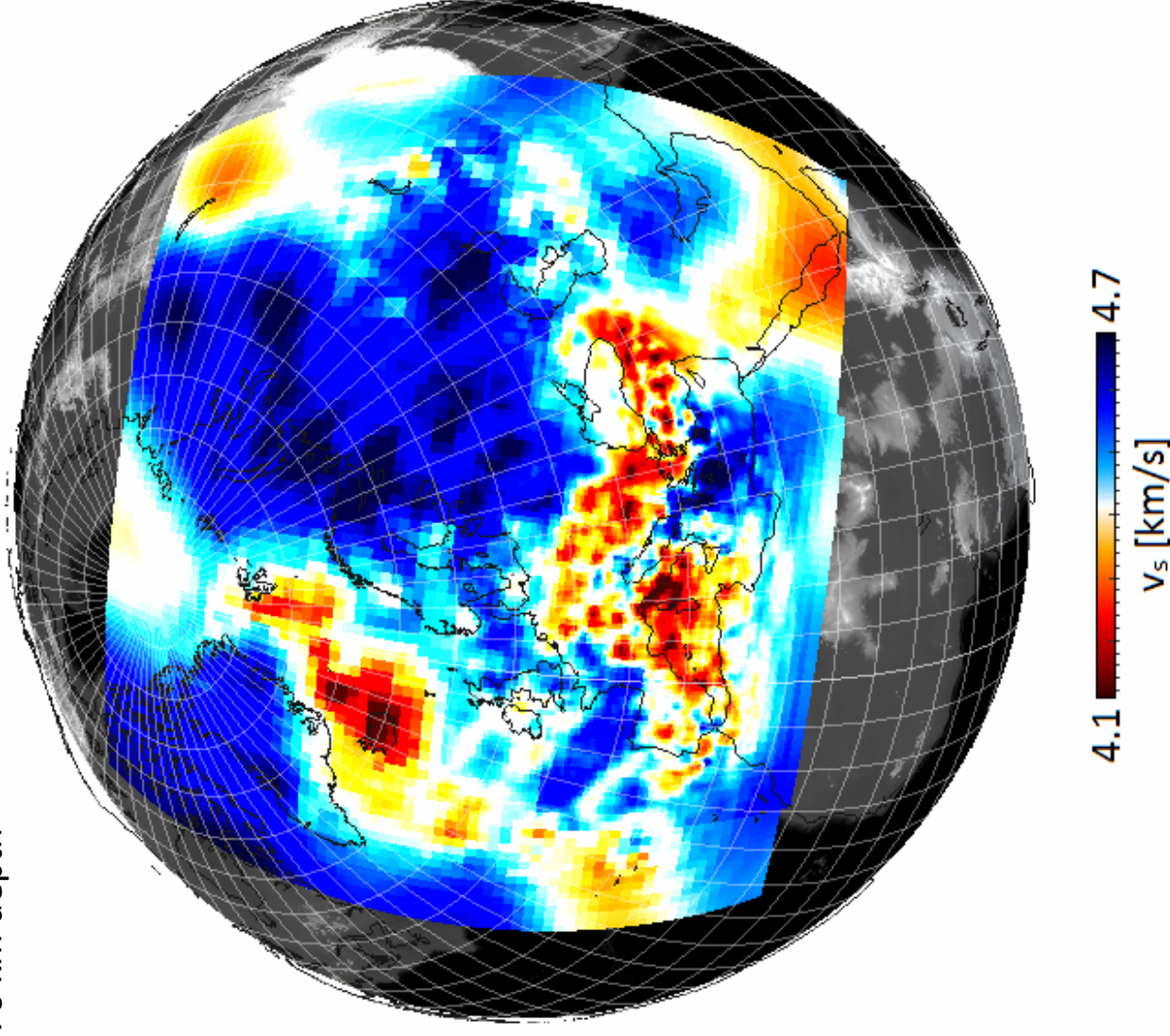
- 113 events,  $\approx 800$  receivers, periods between 8 s and  $\approx 200$  s
- Spectral-element solver of the seismic wave equation
- Measurement of time-frequency misfits on complete seismograms (where possible)
- Adjoint techniques for the computation of Fréchet kernels
- Pre-conditioned conjugate-gradient method for iterative misfit minimisation
- So far: 42 iterations  
1 million CPU hours

# APPLICATION:

70 km depth

## Technical specifications

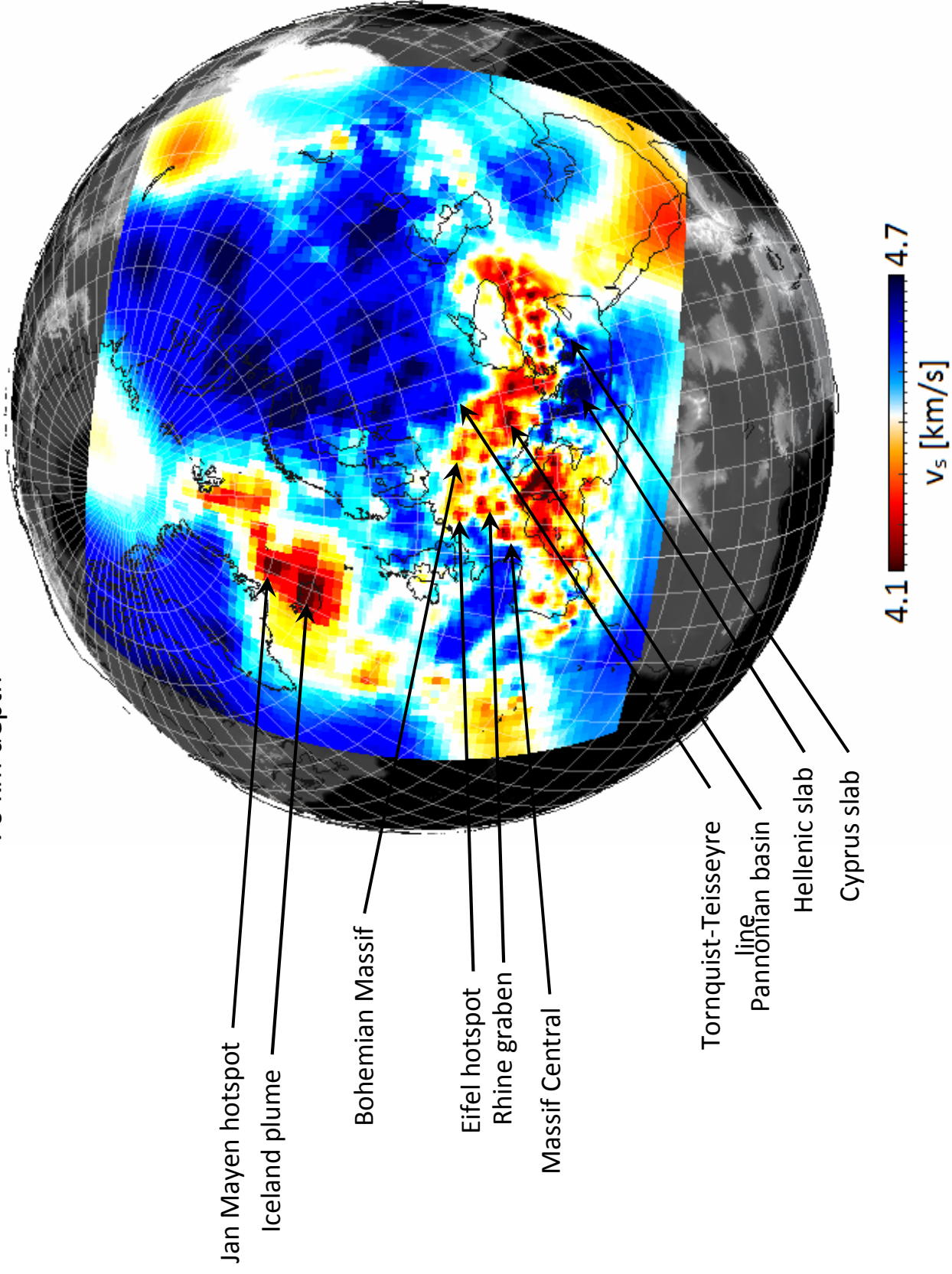
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# APPLICATION:

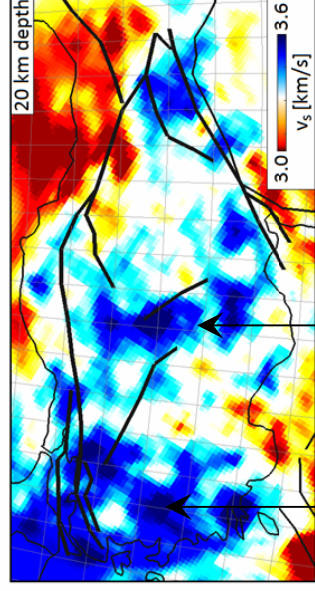
70 km depth





## APPLICATION:

- Simultaneously constrained crustal and mantle structure
- Crustal features: *Menderes Massif, Kirsehir Massif*
- Lithospheric features: *volcanic provinces, North Anatolian Fault Zone*

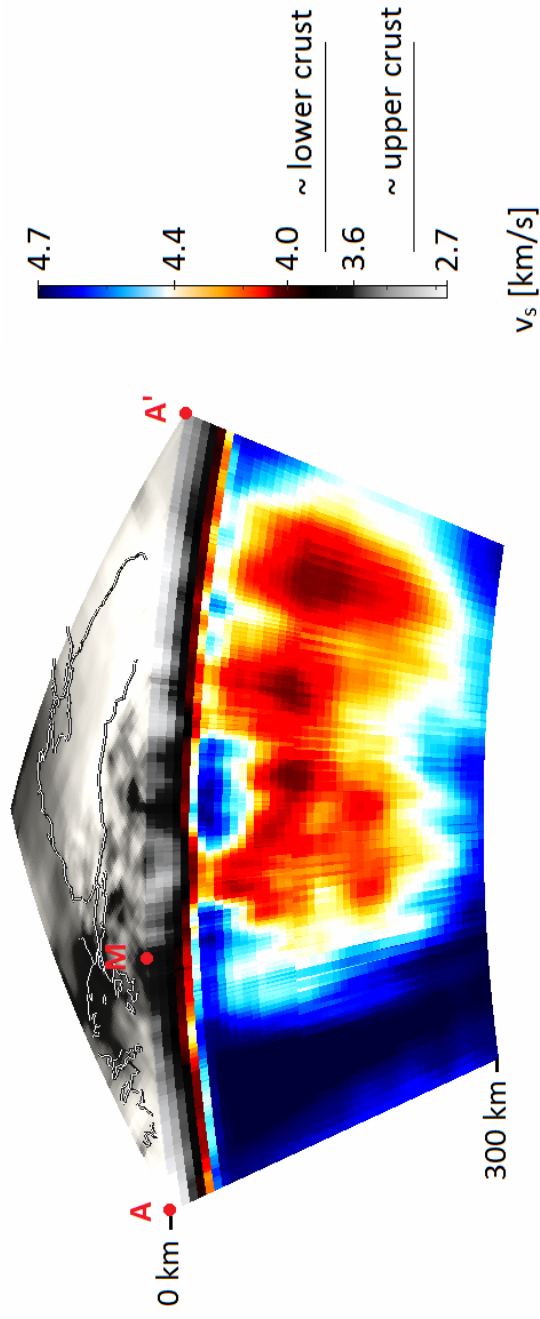
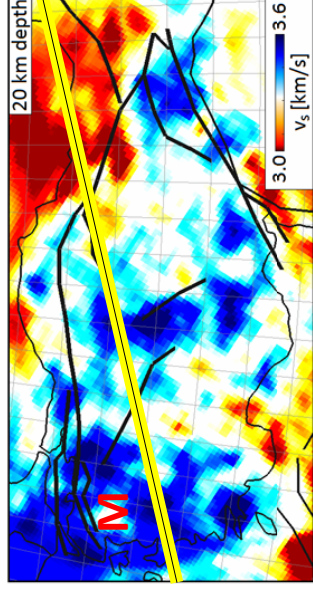


Menderes Massif

Kirsehir Massif

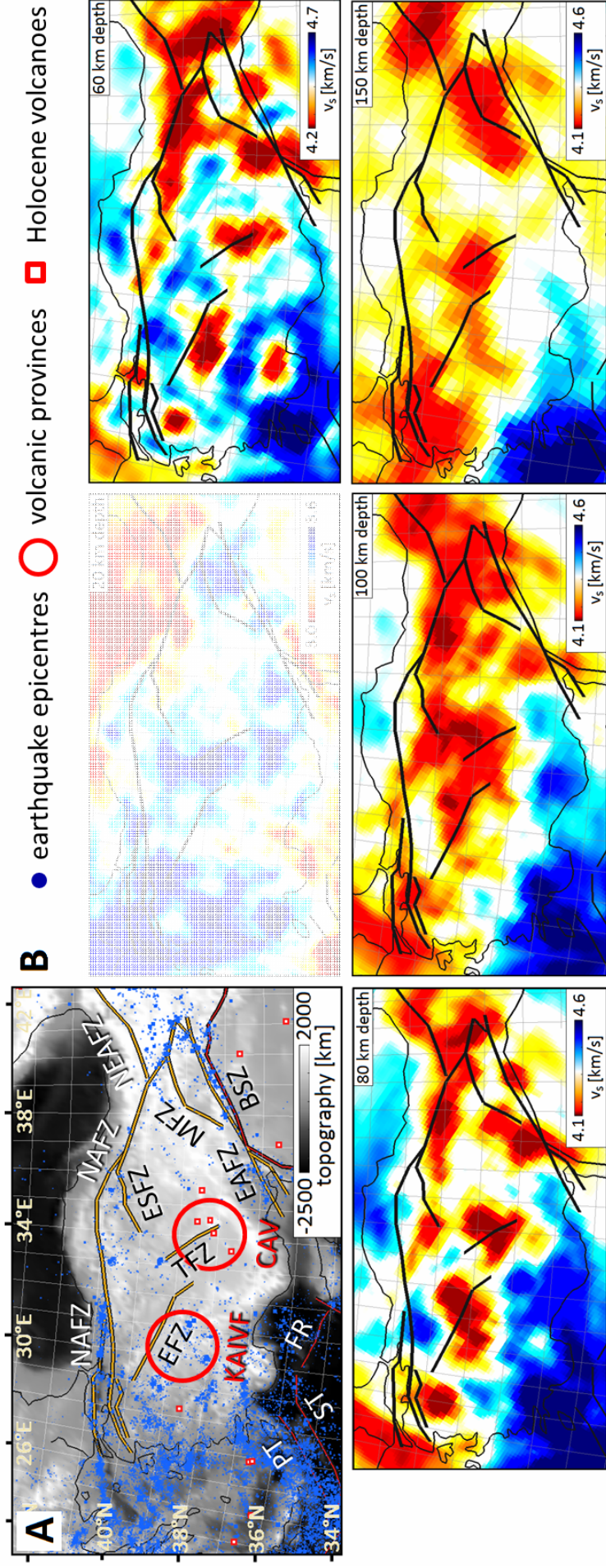
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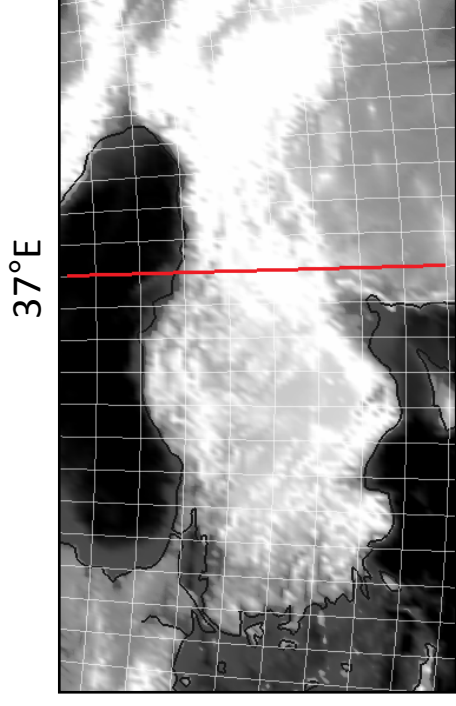
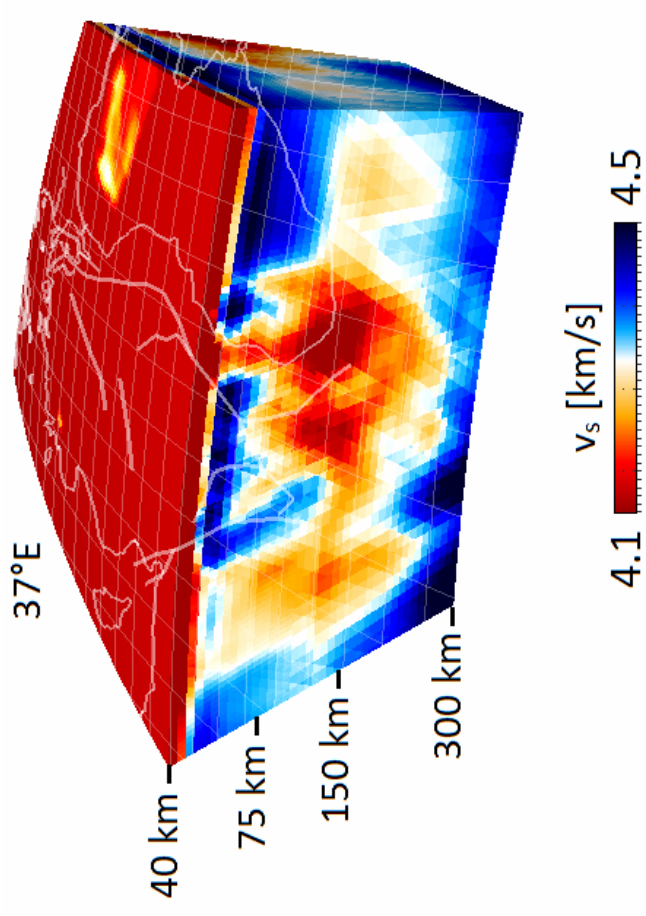
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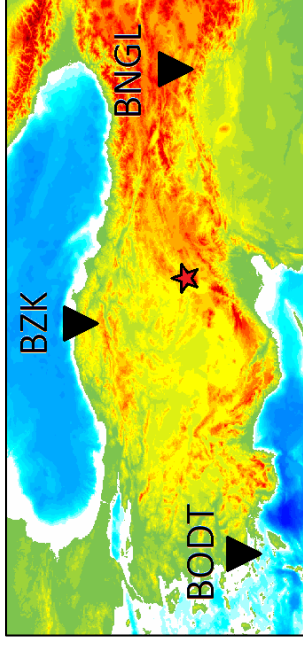
## APPLICATION:

- The North Anatolian Fault Zone
  - not confined to the crust
  - lithospheric feature extending to 80 km depth
  - previously unrecognised crust-mantle interaction

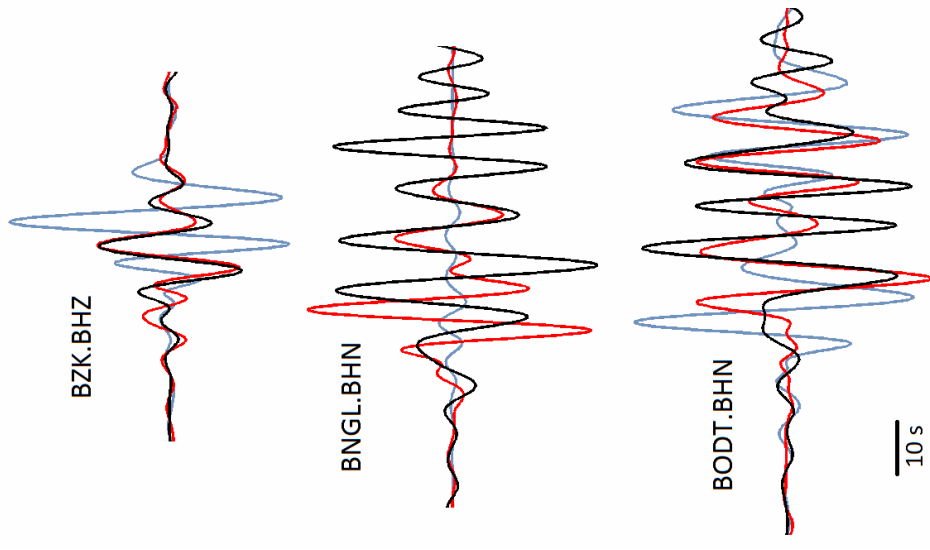


# APPLICATION:

Data fit:



- data
- initial (S2ORTS+crust2.0)
- current (iteration 42)

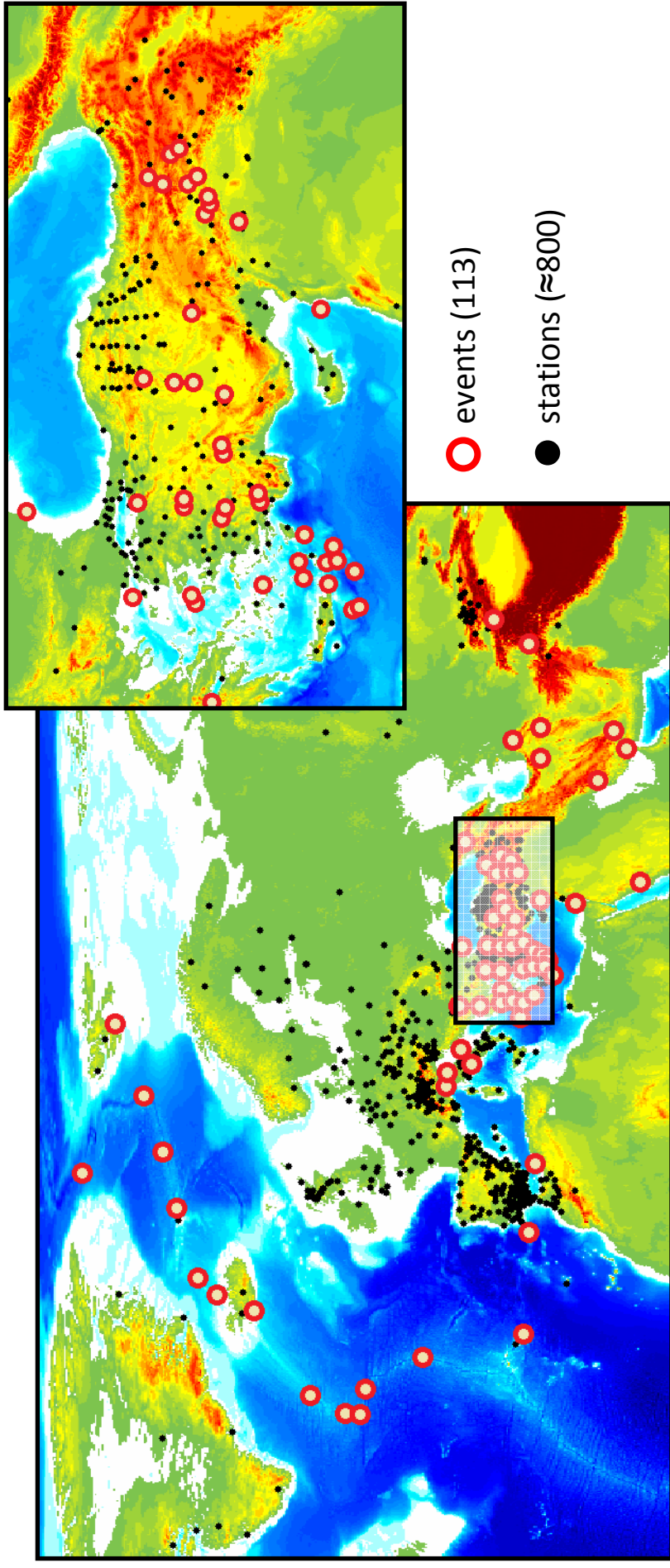




# CONCLUSIONS:

Proof of concept

- multi-scale full waveform inversion
- teleseismic & regional data sets
- invert simultaneously for local and deeper structure
- **key element:** upscaling



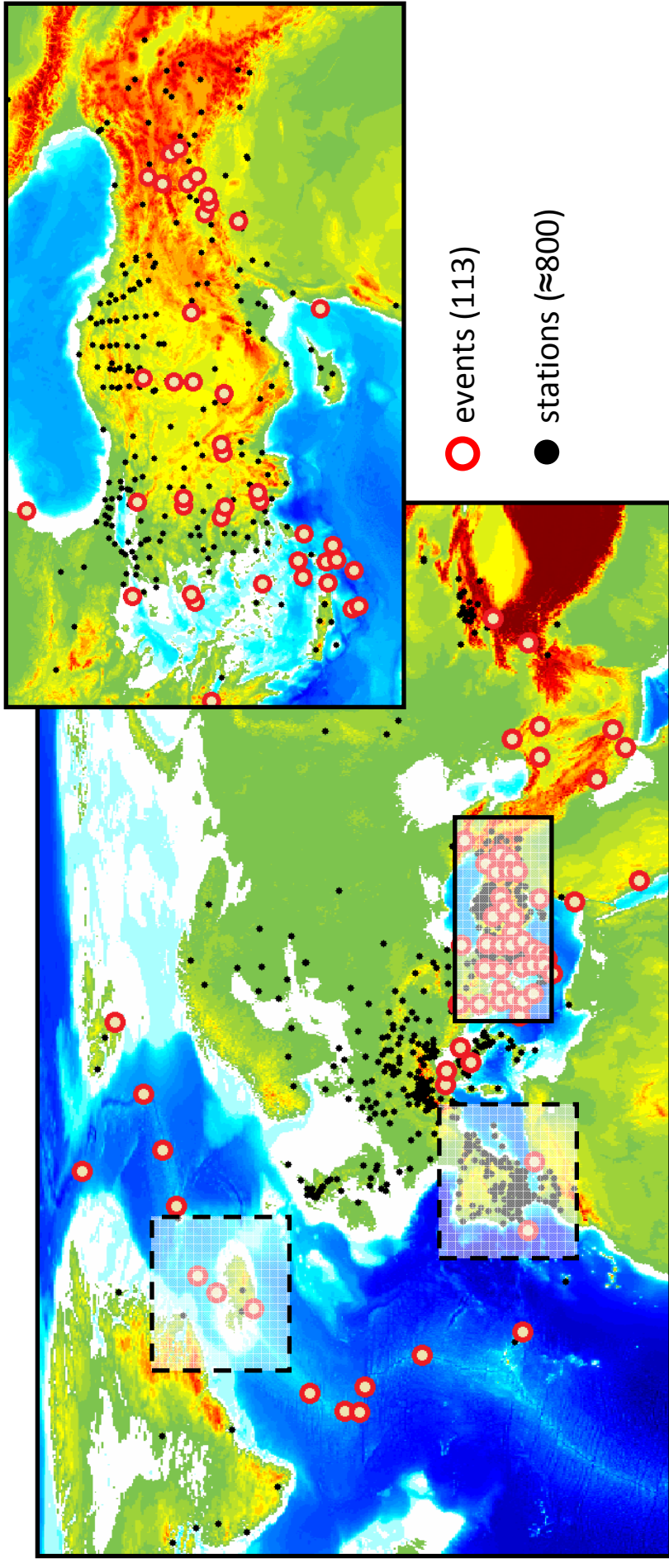
# OUTLOOK:

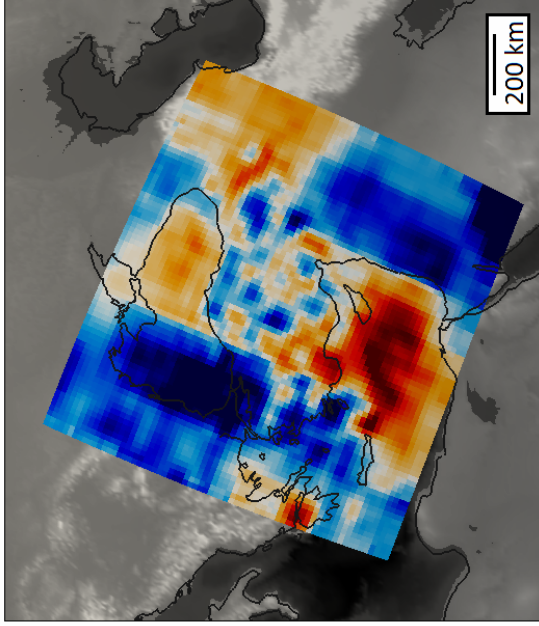
Proof of concept

Further incorporation of regional data sets

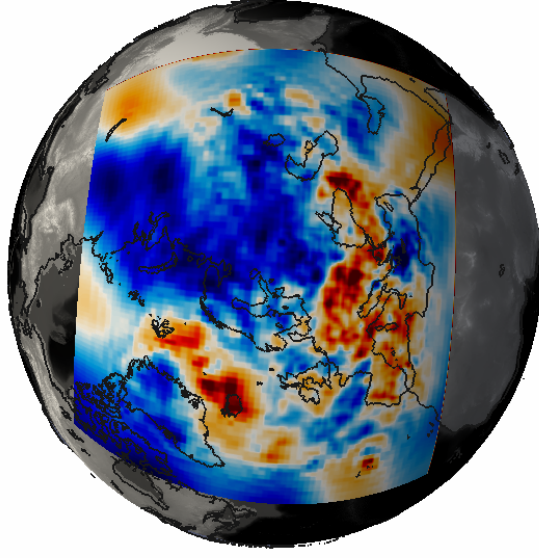
Improvement of upscaling method (3D homogenisation)

## Comprehensive model of Europe & western Asia

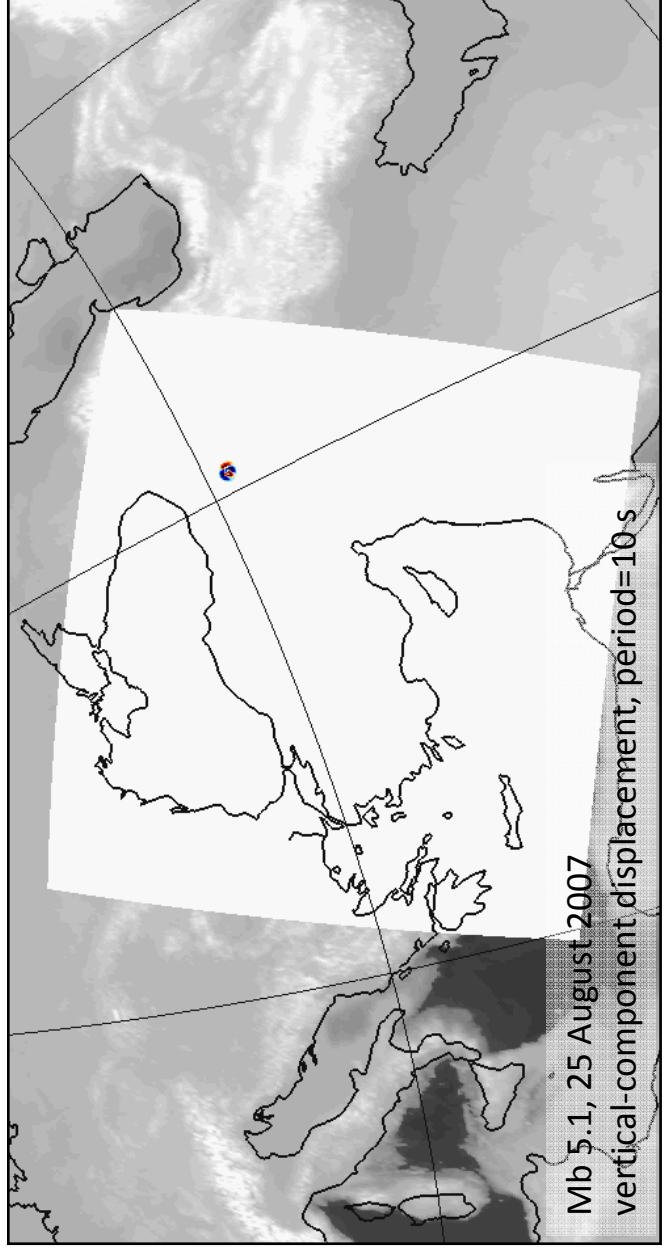




2.8 3.7  
 $v_{sv}@ 20 \text{ km}$  [km/s]

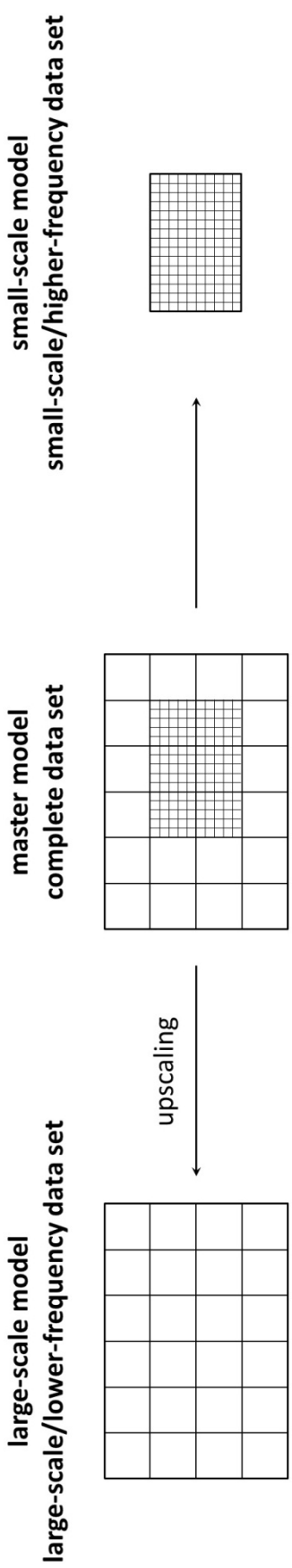


4.05 4.65  
 $v_{sv}@ 100 \text{ km}$  [km/s]

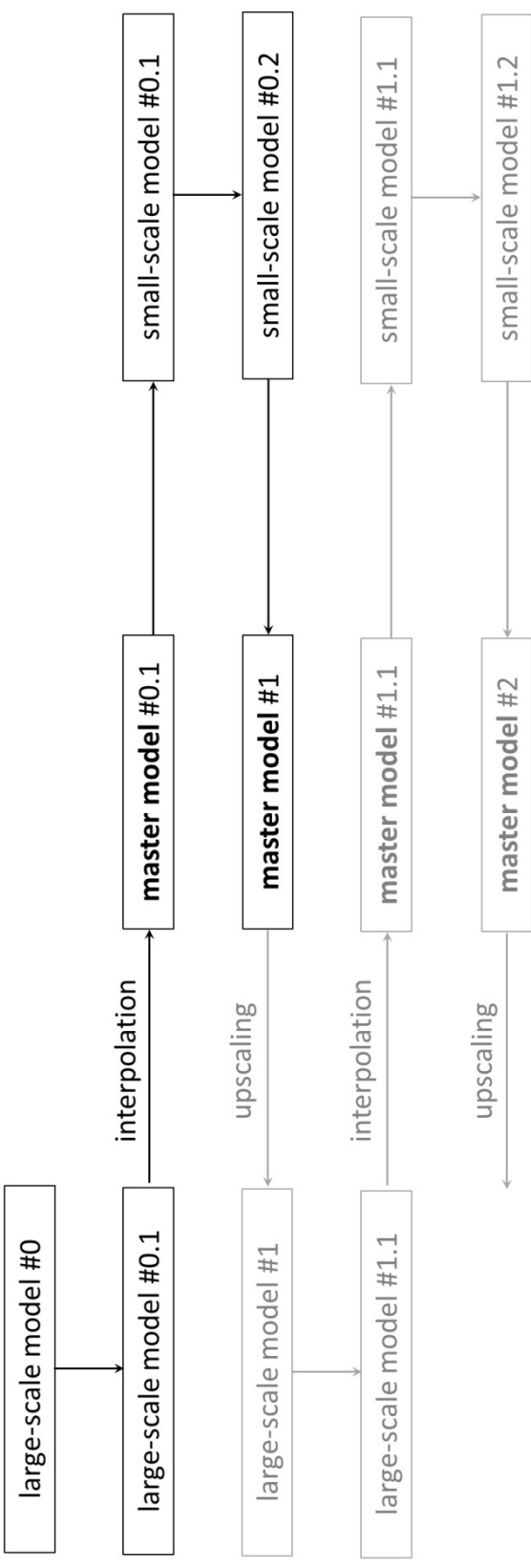


Thanks for your attention!

**MODEL SETUP**

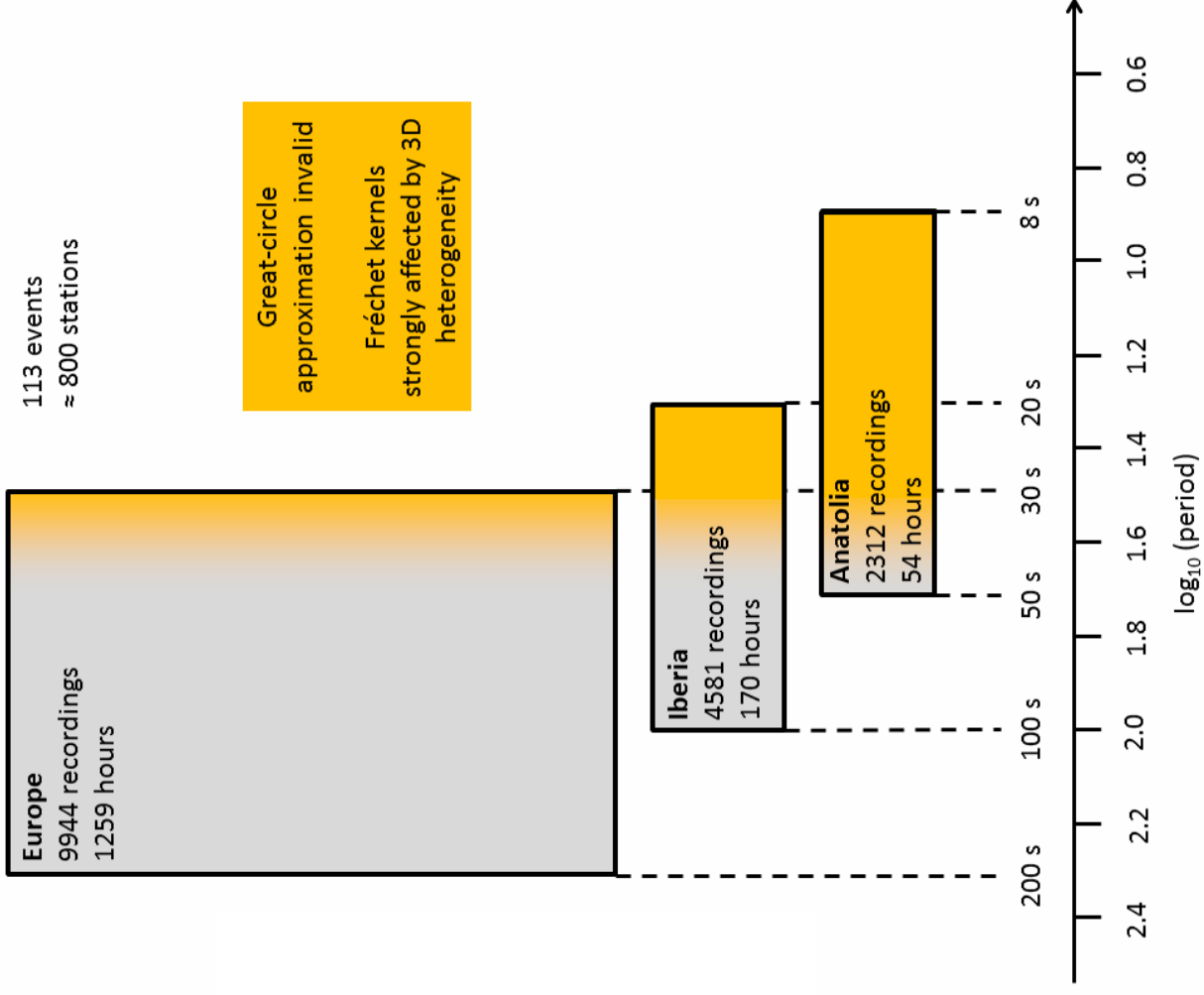


**ITERATIVE INVERSION SCHEME**



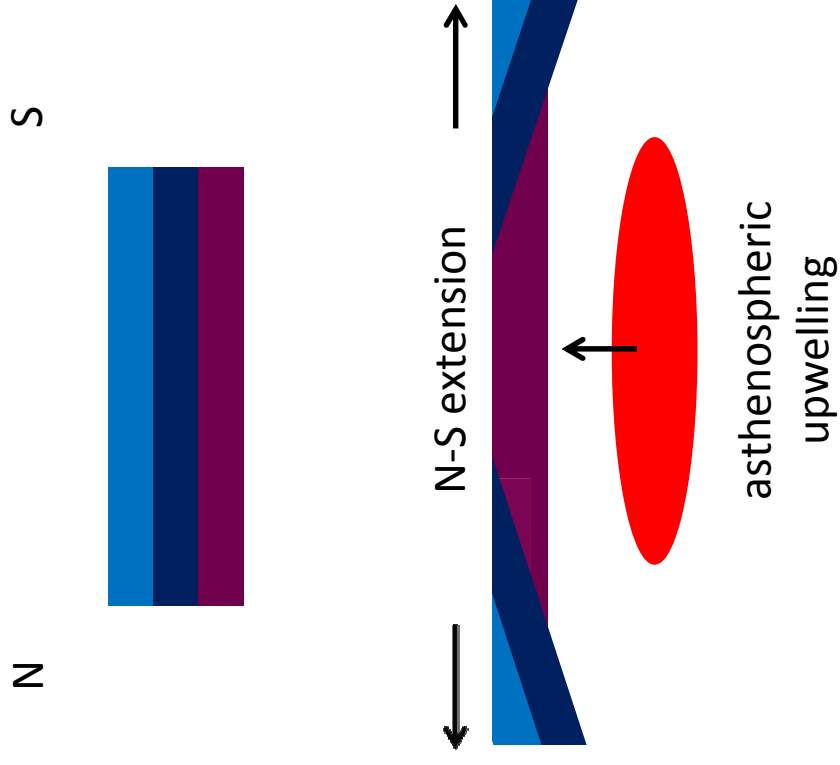
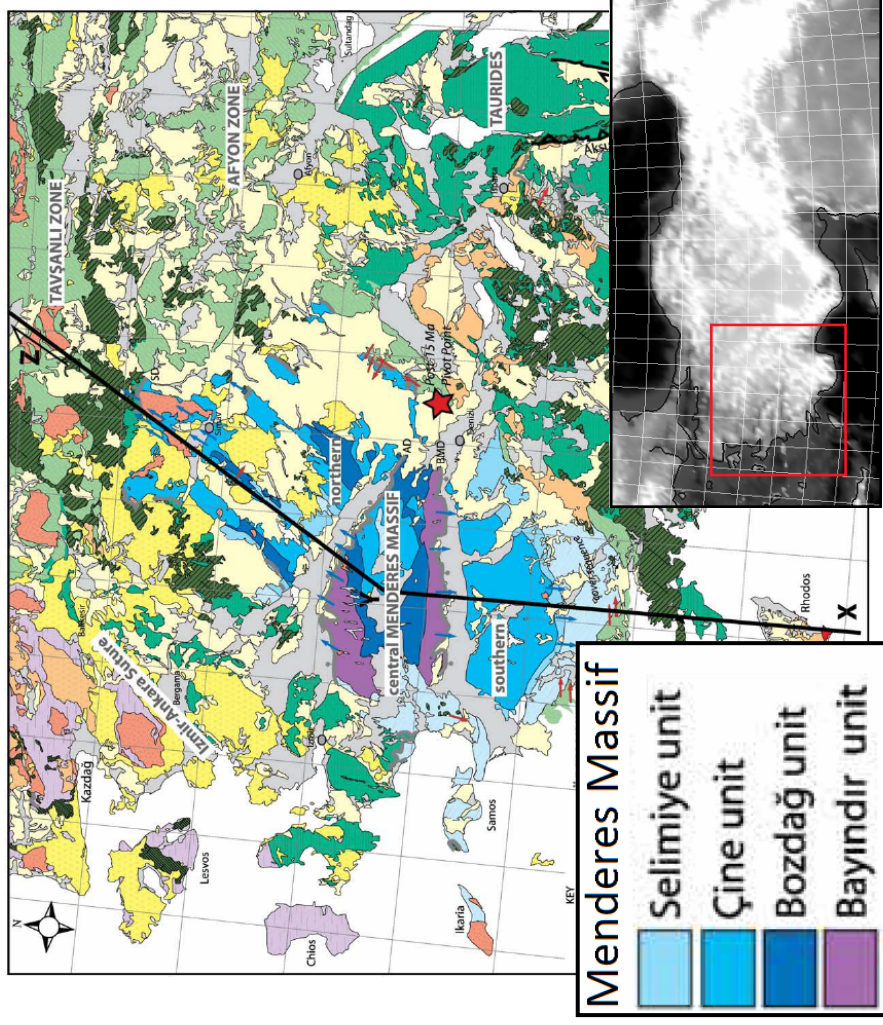


# DATA:



# APPLICATION:

- The Menderes Massif
- extensional outcropping of the lower crust



adapted from *van Hinsbergen et al.* 2010

# APPLICATION:

- The Menderes Massif
  - extensional outcropping of the lower crust
  - confirmed by tomographic model
  - **no** asthenospheric upwelling directly beneath the central Menderes Massif
  - **more complex than a geologic cartoon**

